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Abstract.

Experiment E950 at AGS, BNL has provided data with high statistics for the left-right asymmetry of proton-carbon elastic scattering in the Coulomb-nuclear interference region of momentum transfer. It allows to access information about spin properties of the Pomeron and has practical implications for polarimetry at high energies. Relying on Regge factorization the results for the parameter  $r_5$ , ratio of spin-flip to non-flip amplitudes, is compared with the same parameter measured earlier in pion-proton elastic and charge exchange scattering. While data for  $\text{Im}r_5$  agree (within large systematic errors), there might be a problem for  $\text{Re}r_5$ . The  $\pi N$  data indicate at a rather small contribution of the f-Reggeon to the spin-flip part of the iso-scalar amplitude which is dominated by the Pomeron. This conclusion is supported by direct analysis of data for elastic and charge exchange  $pp$  and  $pn$  scattering which also indicate at a vanishing real part of the hadronic spin-flip amplitude at energies 20 GeV and higher. This is a good news for polarimetry, since the E950 results enhanced by forthcoming new measurements at AGS can be safely used for polarimetry at RHIC at higher energies.

# Small Angle Scattering of Polarized Protons

B.Z. Kopeliovich

## I INTRODUCTION

It is usually assumed that small angle elastic scattering at high energies is dominated by Pomeron exchange. At the same time, definition for the Pomeron varies depending on a model (a Regge pole, pole plus cuts, two-gluon model, DGLAP, BFKL, two-component Pomeron, etc.) what led to a confusion among the community. In what follows, we do not assume any model, unless otherwise specified. We treat the Pomeron as a shadow of inelastic processes. i.e. the dominant contribution to the elastic amplitude which has vacuum quantum numbers in the crossed channel and is related to the main bulk of inelastic channels via the unitarity relation.

Here we are interested in spin properties of such a shadow, namely, the spin-flip part of the elastic  $pp$  amplitude related to the Pomeron. Naively, treating

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FIGURE 1. Data from the E704 experiment at Fermilab [5] (squares) compared to theoretical calculations. Left panel: calculations with  $\rho = 0$ ,  $\delta = 0$  and  $Re r_5 = 0$  for different values of  $-0.8 < Im r_5 < 0.8$ . Thick curve corresponds to  $r_5 = 0$ . Right panel:  $r_5$  correspond to the results of the E950 experiment at BNL [6] as given by (9). Thin curves show the corridor of uncertainty. Round points show results of other experiments, see in [5]. The dashed curve corresponds to  $r_5 = 0$ .

the Pomeron perturbatively, one may expect it to conserve  $s$ -channel helicity as the quark-gluon vertex does. However, even perturbatively a quark gains a substantial anomalous color-magnetic moment which leads to a spin-flip, like it happens in QED in  $g - 2$  experiments. Besides, there are many nonperturbative mechanisms generating a Pomeron spin-flip, which are overviewed in [1].

We will present the results in terms of the parameter  $r_5$  which is defined in [1] and is proportional to ratio of the spin-flip to non-flip forward elastic amplitudes.

$$r_5 = \frac{2m_N \Phi_5}{\sqrt{-t} Im(\Phi_1 + \Phi_3)} , \quad (1)$$

where the helicity amplitudes are defined as,

$$\Phi_1 = \langle ++ | \hat{M} | ++ \rangle ; \quad \Phi_3 = \langle +- | \hat{M} | +- \rangle ; \quad \Phi_5 = \langle ++ | \hat{M} | +- \rangle . \quad (2)$$

Parameter  $r_5$  may vary with energy, in particular, it is expected to rise [2].

In this talk I focus on the best of our knowledge of  $r_5(s)$  which is still a challenge. Importance of this task is two-fold. First of all, it reflects the underlying dynamics and data for  $r_5$  should be compared with numerous and diverse model predictions. Second of all, the polarization program at RHIC needs reliable and fast polarimetry. The currently available polarimeter, is based on the effect of Coulomb-nuclear interference (CNI) [3,4] which is fully predicted theoretically provided that  $r_5$  is known.

## II CNI REVISITED

It is not easy to access the spin-flip part of the Pomeron amplitude since it hardly contributes to single spin asymmetry  $A_N(t)$ . Indeed, although the Pomeron is not a Regge pole, but if  $r_5$  does not vary steeply with energy, one should not expect a large phase shift between the spin-flip and non-flip parts of the Pomeron amplitude. Of course  $r_5$  can be extracted from spin correlation  $A_{SL}$  which is, however, difficult to measure.

A unique source of a spin-flip amplitude with a right phase (i.e. with about  $90^\circ$  phase shift) is Coulomb scattering. This real amplitude proportional to

the anomalous magnetic momentum of proton, interferes with the imaginary non-flip part of the Pomeron amplitude leading to a sizeable spin asymmetry  $A_N$  which is nearly independent of energy. The latter fact, as well as possibility to predict the effect, are crucial for polarimetry at high energy.

If the spin-flip part of the Pomeron amplitude were zero, the CNI contribution to single spin asymmetry would be fully predicted [3],

$$A_N(t) = \frac{4(t/t_p)^{3/2}}{3(t/t_p)^2 + 1} A_N(t_p) . \quad (3)$$

Here

$$t_p = -8\sqrt{3} \frac{\pi \alpha}{\sigma_{tot}^{pp}} , \quad (4)$$

is the position of the maximum of  $A_N(t)$  which is equal to

$$A_N(t_p) = \frac{\sqrt{-3t_p}}{4m_N} (\mu_p - 1) , \quad (5)$$

where  $\mu_p - 1 \approx 1.79$  is the anomalous magnetic moment of the proton.

Predictions for  $A_N(t)$  [3] shown by thick curve in Fig. 1 (left panel) are compared with data from the experiment E704 at 200 GeV [5]. Apparently, agreement is good, although the error bars are quite large.

One may conclude that CNI provides a perfect absolute polarimeter which can be safely used at high energies. Life, however, is more difficult, but also more exciting. The Pomeron amplitude may have a nonzero spin-flip part  $r_5$  which affects the spin asymmetry [7,8]. Fig. 1 (left panel) demonstrates how  $A_N(t)$  varies versus  $Im r_5$  assuming  $Re r_5 = 0$ .

Such a sensitivity to  $r_5$  of the CNI effects leads to two-fold consequences:

- CNI polarimetry turns out to be less certain than has been originally expected;
- $A_N$  in the CNI region is an observable maximally sensitive to  $r_5$  and can be used to determine the magnitude of the Pomeron spin-flip.

### III CNI WITH NUCLEAR TARGETS: THE E950 EXPERIMENT

In order to make use of a CNI polarimeter one should first of all calibrate it, i.e. perform measurements of  $r_5$  with proton beams or target with known polarization. Such beams are available at AGS, but only at energies not much above 20 GeV. In this energy range contribution of the sub-leading Reggeons is still important and can substantially contribute to  $r_5$  giving it a steep energy dependence. It would be too risky to rely on a value of  $r_5$  measured at these

energies for polarimetry at much higher energies. Especially dangerous are the iso-vector Reggens  $\rho$  and  $a_2$  which are spin-flip dominated. To get rid of these unwanted contributions it was suggested in [9] to use CNI on iso-scalar nuclei, in particular carbon. However, two important questions were raised:

- Can one use  $r_5$  measure on nuclear target for polarimetry in  $pp$  scattering?
- How should expression for CNI asymmetry be modified in the case of nuclear target?

As for the first question, it has been known since 50s [10] that  $r_5$  remains unchanged, if to treat nuclear effects within the optical model. An updated proof and discussion of possible corrections can be found in [11], as well as the expression for  $r_5$  on a nuclear target,

$$r_5^{pA}(t) = \frac{1 - i\rho_{pA}(t)}{1 - i\rho_{pN}} r_5^{pN} \quad (6)$$

Here  $\rho_{pN}$  is the ratio of real to imaginary parts of the forward elastic  $pN$  amplitudes. We keep  $t$ -dependence of  $\rho_{pA}(t)$  since it might be quite steep within the CNI range of  $t$ .

The CNI effects for nuclei are substantially modified by nuclear formfactors [9,11] which are steep functions of  $t$

$$\begin{aligned} \frac{16\pi}{(\sigma_{tot}^{pA})^2} \frac{d\sigma_{pA}}{dt} A_N^{pA}(t) &= \frac{\sqrt{-t}}{m_N} F_A^h(t) \left\{ F_A^{em}(t) \frac{t_c}{t} [(\mu_p - 1)[1 - \delta_{pA}(t) \rho_{pA}(t)] \right. \\ &\quad \left. - 2[Im r_5^{pA}(t) - \delta_{pA}(t) Re r_5^{pA}(t)] \right\} - 2 F_A^h(t) [Re r_5^{pA}(t) - \rho_{pA}(t) Im r_5^{pA}(t)] \quad (7) \end{aligned}$$

where

$$\begin{aligned} \frac{16\pi}{(\sigma_{tot}^{pA})^2} \frac{d\sigma_{pA}}{dt} &= \left( \frac{t_c}{t} \right)^2 [F_A^{em}(t)]^2 - 2[\rho_{pA}(t) + \delta_{pA}(t)] \frac{t_c}{t} F_A^h(t) F_A^{em}(t) \\ &\quad + \left[ 1 + \rho_{pA}^2(t) - \frac{t}{m_p^2} |r_5^{pA}(t)|^2 \right] [F_A^h(t)]^2. \quad (8) \end{aligned}$$

Here  $t_c = -8\pi\alpha/\sigma_{tot}^{pA}$ ;  $\delta_{pA}(t)$  is the Coulomb phase for  $pA$  scattering calculated in [12] with high accuracy; the ratio of real to imaginary parts of the  $pA$  amplitude,  $\rho_{pA}(t)$  and nuclear formfactors, electromagnetic  $F_A^{em}(t)$  and hadronic  $F_A^h(t)$ , are calculated in [12] with a realistic nuclear density.

A first time precise measurement of  $A_N^{pA}(t)$  performed by the E950 collaboration for proton-carbon elastic scattering with 22 GeV polarized beam at AGS [6]. The authors fitted the data with expressions (7)-(8) and found

$$Im r_5 = -0.161 \pm 0.226; \quad Re r_5 = 0.088 \pm 0.058. \quad (9)$$

FIGURE 2. The data from [6] with statistical and systematic errors summed quadratically, while the uncertainty in the beam polarization is treated and an overall normalization.

The authors added linearly the errors, statistical one and two systematic related to the row asymmetry and the beam polarization. The resulting error seems to be overestimated and may be treated as an upper bound. I have repeated the fit adding quadratically the first two errors, but treating the error in the beam polarization as an overall normalization. I have arrived to similar central values of the parameters, but smaller errors which might be treated as a lower bound,

$$\text{Im} r_5 = -0.156 \pm 0.170; \quad \text{Re} r_5 = 0.084 \pm 0.042 . \quad (10)$$

The renormalization factor for the beam polarization was found to be  $N = 1.001 \pm 0.120$ . The result of the fit and fitted data are depicted in fig. 2

Note that this values of  $r_5$  correspond to the iso-scalar part of elastic  $pp$  amplitude. As far as it is known (with a considerable uncertainty) at energy 22 GeV one may consider using it for polarimetry at higher energies. This would be appropriate if energy variation of the Pomeron part of  $r_5$  is small and if the sub-leading iso-scalar Reggeon ( $\omega$  and  $f$ ) contribution to  $r_5$  is small at 22 GeV. The latter assumption has been questioned recently and possible corrections for polarimetry are discussed in [8].

Assuming no energy dependence of  $r_5$  one can use (9) to predict  $A_N^{pp}$  at energy 200 GeV and compare with the E704 data (including data at larger  $t$ , see [5]), as is depicted in Fig. 1 (right panel) by thick solid curve, while the corridor related to the errors in (9) is shown by thin solid curves. In spite of large uncertainties in (9) one may conclude that data do not support such a prediction. Of course this comparison is based of unjustified assumption of no energy dependence of  $r_5$ , nevertheless, the observed disagreement should be considered as a warning.

## IV REGGE FACTORIZATION: ANALYSIS OF $\pi N$ DATA

The iso-scalar part of  $r_5^{NN}$  extracted from  $pA$  may be compared with  $\pi N$  data. They should be related provided Regge factorization holds. Amplitude analyses of  $\pi N$  elastic and charge exchange scattering up to energy 40 GeV are available [13] and the results contain  $r_5(t)$  for iso-scalar part of the scattering amplitude. It turns out that all the analyses demonstrate no  $t$ -dependence of  $r_5(t)$  within error bars for  $|t| < 0.5 \text{ GeV}^2$ , what is not surprising since the  $\sqrt{-t}$  factor is removed. In order to reduce uncertainties data for iso-scalar  $r_5(t)$  for each analysis was fitted by a constant within this  $t$ -interval. The results for  $\text{Im} r_5$  are depicted in Fig. 3 by round points, while the E950 value is shown by a square.

[height=.3]im [height=.3]re

FIGURE 3. Comparison of the results of the E950 experiment at BNL (square points) with the results of amplitude analyses [13] of  $\pi N$  data. Left panel: data for  $Im r_5$  are shown by full round dots. Right panel: round dots show the phase uncorrected results of [13] for  $Re r_5$ , star points are corrected for the phase of the non-flip amplitude.

Apparently, the  $\pi N$  data prefer negative  $Im r_5$ , however they do not specify energy dependence. Within large error bars they are consistent either with no energy dependence, or with  $Im r_5$  rising with energy. The former case would correspond to a net contribution of the Pomeron spin-flip, while the latter possibility would mean that  $f$ -Reggeon contribution to  $Im r_5$  exists and is negative. Thus, we conclude that  $Im r_5^f \leq 0$ . Since the phase of the  $f$ -amplitude is given by the signature factor,  $\eta(t) = i - \cot[\pi\alpha_f(t)/2]$  we should expect from this consideration that  $Re r_5^f \geq 0$ .

Data for  $Re r_5$  extracted from the same analyses [13] are depicted by round points in Fig. 3 (right panel). The real part of the spin flip amplitude was determined in those analyses relative to the imaginary part of the non-flip amplitude, i.e. assuming it pure imaginary. Thus, one should introduce a correction for a nonzero real part of the non-flip amplitude,  $\Delta Re F_{+-} = \rho_{\pi N} Im F_{+-}$ . Using  $Im r_5$  found above, new corrected values for  $Re r_5$  were determined and plotted in Fig. 3 (right panel) by star points. These results are in agreement with the above expectation  $Re r_5^f \geq 0$ , preferring, however, zero and energy independent value. The point from the E950 experiment shown by a square is somewhat higher, but still is compatible with these results.

Thus, available amplitude analyses of  $\pi N$  data at energies 6 – 40 GeV indicate at the dominance of the Pomeron amplitude with

$$Im r_5 \approx -0.12; \quad Re r_5 \approx 0, \quad (11)$$

and vanishing contribution of the  $f$ -Reggeon.

## V COMPARISON WITH THEORETICAL EXPECTATIONS

One can find in the literature a variety model predictions for the spin-flip part of the Pomeron amplitude. Many of them are collected and discuss in [1]. Here we list them briefly mentioning the underlying physical ideas.

- Treating the gluon-quark vertex as an analog to the iso-scalar photon-proton one can relate the anomalous color-magnetic moment of a quark to the iso-scalar part of the anomalous magnetic momentum of the proton [14]. After installation of such a quark-gluon vertex into the two-gluon model for the Pomeron one gets [14],  $Im r_5 = 0.13$ . Although the order of magnitude is correct, the sign is opposite to data presented in Fig. 3.

- Helicity of the proton is not equal to the sum of quark helicities. Therefore, the proton may flip its helicity even if quarks do not (as the leading order pQCD predicts). A quark-diquark model of the proton leads to nonzero  $Im r_5 = -(0.05 - 0.15)$ , dependent on the diquark size  $(0.5 - 0.2 \text{ fm})$  [7]. Within the uncertainty this prediction agrees with the data.
- Modeling the Pomeron-proton coupling via two pion exchange [15,16] one arrives at a conclusion that iso-scalar Reggeons ( $\mathbb{P}$ ,  $f$ ,  $\omega$ ) are predominantly spin non-flip, while iso-vectors ( $\rho$ ,  $a_2$ ) mostly flip the proton spin. Prediction of [16] for the Pomeron is  $Im r_5 = 0.06$ , what has incorrect sign. A similar pion cloud model developed [17] with some differences in details predicts  $Im r_5 = -0.3$ ,  $Re r_5 = -0.06$ , what also disagree with the data.
- The phenomenological model [18] assuming that the spin-flip part can be deduced from the impact parameter distribution of matter in the proton and fitted to data predicts correct sign,  $Im r_5 \approx -(0.01 - 0.02)$ , but modulo too small value.

One should not treat this comparison as a way to confirm or reject models. None of the models under discussion may pretend to be a dominant mechanism. The dynamics suggested by other models can contribute as well.

Note that analysis of  $pp$  elastic data performed in [19] led to parameters  $Im r_5 = -0.054$  which is too small, but has the right order of magnitude and correct sign compared to data plotted in Fig. 3. The analysis performed in [19] was based on a specific modeling of the odderon amplitude which introduces a strong sensitivity of polarization to  $r_5$ . Besides, the contribution of the sub-leading Reggeons largely contributing to  $r_5$  ( $\rho$ ,  $a_2$ ) was neglected, instead this contribution was attributed to the Pomeron.

## VI $\pi N$ VS E950 DATA: HOW SHAKY IS THE THEORY BRIDGE?

The results of amplitude analyses of  $\pi N$  data are good news for polarimetry at RHIC. Absence of energy dependent contribution of iso-scalar sub-leading Reggeons to  $r_5$  suggested by the data would allow one to use the result of measurement of  $A_N$  by the E950 experiment for polarimetry at higher RHIC energies. However, the central value of  $Re r_5$  which follows from the E950 data is different from zero and indicates that the Reggeon contribution might be important. Then, one may expect  $r_5$  to vary with energy and the polarimetry gets an uncertainty.

Moreover, the fitting parameters  $Re r_5$  and  $Im r_5$  strongly correlate as it is demonstrated in [6]. For example, if to enforce and fix  $Re r_5 = 0$ , the  $\chi^2$



doubles and  $Im r_5$  changes sign. Thus, it is difficult to bring together the results of study of different reactions  $\pi N$  and  $pC$ .

Facing such a problem one should check how reliable are assumptions done in order to make a link between iso-scalar amplitudes in  $pp$  and  $\pi N$  scattering.

1. First of all, how precise is factorization connecting  $r_5$  in  $pp$  and  $\pi N$ ? In all the models listed above it is provided. Even in the two-gluon model which does not obey Regge factorization,  $r_5$  must be the same for  $\pi N$  and  $pp$ . It is known, however that that Regge cuts corresponding to eikonal multi-Pomeron rescatterings violate Regge factorization. However, as is discussed above and proven in [10] these corrections do not alterate  $r_5$ .
2. Only sub-leading Reggeon,  $f$ , contributes to the iso-scalar amplitude in  $\pi N$  scattering, while both  $f$  and  $\omega$  are present in  $pp$ . Moreover, in order to respect duality  $f$  and  $\omega$  should be exchange degenerate, i.e. their contributions are expected to add up in  $Re r_5$  and nearly cancel in  $Im r_5$ . This is different from  $\pi N$  where  $f$ -Reggeon should contribute equally to  $Re r_5$  and  $Im r_5$ . However, this difference does not explain the observed difference between  $\pi N$  and  $pp$ . If  $f$ -Reggeon does not contribute to  $r_5$  in  $\pi N$ , according to factorization and exchange degeneracy both the  $f$  and  $\omega$  contributions to  $pp$  must be zero as well.

Although we did not find any good reason to disbelieve the theoretical link between  $\pi N$  and  $pp$ , it is still possible that this is the origin of the problem. On the other hand the observed contradiction is not dramatic since the errors of the E950 data are pretty large. In order to progress further, the accuracy of  $A_N$  in  $pC$  elastic scattering should be improved.

## VII DIRECT INFORMATION FROM NN DATA

There is another narrow place in the theoretical bridge between  $\pi N$  and  $NN$  reactions: it might be a contribution to  $NN$  of sub-leading Reggeons which are forbidden for  $\pi N$ . For instance, besides  $\omega$  there might be other iso-scalar mesons which are suppressed or forbidden (e.g. have negative  $G$ -parity) for  $\pi n$  scattering. This was suggested in [20] as  $\epsilon(0^{++})$  and  $\omega'(1^{--})$  exchange degenerate Reggeons. Indeed, analysis [21] of data for  $pp$  and  $np$  elastic scattering up to 12 GeV shown in Fig. 4 demonstrates an iso-scalar spin-flip  $NN$  amplitude (left panel) which falls with energy much steeper than iso-vector one (right panel). The iso-scalar Regge trajectory turns out to be displaced by one unit down compared to the  $\rho$ -Reggeon trajectory:  $\alpha_\epsilon(t) = \alpha_\rho(t) - 1 = -0.5 + 0.9t$  [21].

It is important to establish whether the large value of  $Re r_5$  observed by the E950 experiment is related to the tail of this low-energy mechanism. If so, then  $Re r_5$  will steeply vanish at higher energies what should affect the

[height=.3]NN

FIGURE 4. Dependence of the spin-flip amplitude on lab momentum for iso-scalar (left panel) and iso-vector (right panel) exchanges. Points are the result of the analysis of data on elastic and charge-exchange  $pp$  and  $pn$  scattering performed in [21] for different bins in  $t$ , and the curves are the results of Regge fit.

polarimetry. In this case the shape of  $A_N(t)$  in the CNI region would change substantially (not supported by preliminary data at 100 GeV).

One can estimate such a low-energy contribution to  $r_5$  at 20 GeV relying on the extrapolation of the iso-scalar spin-flip  $NN$  amplitude done in [21] depicted in Fig. 4. The iso-scalar amplitude is determined by measurement of  $A_N$  and cross sections of elastic and charge-exchange  $pp$  and  $pn$  scattering,

$$N_{1\perp}^0 = \left[ (A_N \sigma)_{pp} + (A_N \sigma)_{pn} - \frac{1}{2} (A_N \sigma)_{cex} \right] / (4 |N_0^0|), \quad (12)$$

where  $|N_0^0|^2 = (\sigma_{pp} + \sigma_{pn})/2$ . At  $t = -0.15$  this amplitude is predicted to be,  $N_1^0 \approx 0.03 \sqrt{\text{mb}}/\text{GeV}$ . The non-flip amplitude equals to  $N_0^0 \approx \sigma_{tot}/(4\sqrt{\pi}) \exp(5t) \approx 4.2 \sqrt{\text{mb}}/\text{GeV}$ . Taking into account the factor  $\sqrt{-t}/m_N$  in  $N_1^0$ , one arrives at the estimate at  $t = -0.15 \text{ GeV}^2$ ,

$$\text{Re } r_5(p_{lab} = 22 \text{ GeV}/c) \approx 0.02, \quad (13)$$

which is too small to explain the value of  $\text{Re } r_5$  in (9).

This estimate agrees well with the measurements of single-spin asymmetry in  $pp$  and  $pn$  performed at 24 GeV at BNL [22]. Neglecting the small charge-exchange contribution (it steeply falls with energy) in (12) one gets at  $t = -0.15 \text{ GeV}^2$ ,

$$\text{Re } r_5(p_{lab} = 24 \text{ GeV}/c) = 0.016 \pm 0.010, \quad (14)$$

Thus, both extrapolation of Argonne data to higher energies and direct measurements at AGS at 24 GeV confirm that  $\text{Re } r_5$  is about order of magnitude smaller than what follows from the E950 data.

It is also very improbable that  $r_5(t)$  could vary substantially at  $0 < -t < 0.15 \text{ GeV}^2$ . As it was mentioned above, in  $\pi N$  data  $r_5$  remains unchanged up to  $-t = 0.5 \text{ GeV}^2$ .

## VIII CONCLUSIONS AND OUTLOOK

The E950 experiment has provided first high statistics measurements for CNI asymmetry in proton-carbon elastic scattering. On the one hand, these data bring information about the spin-flip part of the hadronic amplitude which is tempting to associate with the Pomeron. On the other hand, if

it true, one can use the found parameters for  $r_5$  to predict  $A_N(t)$  at higher energies and use  $pC$  scattering as a polarimeter at RHIC.

At the same time, amplitude analysis of data for  $\pi N$  and  $NN$  elastic and charge-exchange scattering allow to single out the iso-scalar part of the spin-flip amplitude. The values of  $Re r_5$  extracted from these data are sufficiently small to be neglected. This is a great news for the CNI polarimetry which can be safely used at high energies. This value of  $Re r_5$  is, however, much smaller than found from the E950 data. To resolve this controversy one needs new and more precise data for CNI spin asymmetry and in a wider energy range.

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